

Probing Higgs Couplings in $e^+e^- \rightarrow \gamma\gamma\gamma$.

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Abstract

We investigate the existence of anomalous Higgs boson couplings, $H\gamma\gamma$ and $HZ\gamma$, through the analysis of the process $e^+e^- \rightarrow \gamma\gamma\gamma$ at LEP2 energies. We suggest some kinematical cuts to improve the signal to background ratio and determine the capability of LEP2 to impose bounds on those couplings by looking for a Higgs boson signal in this reaction.

I. INTRODUCTION

The predictions of Standard Model (SM) for the structure of the fermion–vector boson couplings have been exhaustively tested in the last few years. In particular, the recent data of LEP1 at the Z -pole [1] have confirmed with a unprecedented degree of precision the properties of the neutral weak boson and its vector and axial couplings with the different fermion flavors. Nevertheless, we do not have the same level of confidence on other sectors of the SM, like the self-couplings among the vector bosons and the Higgs boson couplings with fermions and bosons. The determination of these interactions can either confirm the non-abelian gauge structure of the theory and the mechanism of the spontaneous breaking of the electroweak symmetry or provide some hint about the existence of new physics beyond the SM.

A convenient way to parameterize possible deviations of the SM predictions is through the effective theory approach [2]. In this scenario, we assume that the existence of new physics, associated to a high-energy scale Λ , can manifest itself at low energy via quantum corrections, where the heavy degrees of freedom are integrated out. These effects are then described by effective operators involving the spectrum of particles belonging to the low-energy theory, *i.e.* the usual fermions and bosons.

In the linear representation, a general dimension six effective Lagrangian can be written as,

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n \quad (1)$$

where the operators \mathcal{O}_n involve simultaneously both vector boson and Higgs boson fields which share the same coefficients f_n . Therefore, the study of anomalous Higgs boson couplings can be an important tool to investigate the effect of new physics and concomitantly furnish information about the self-coupling of the vector bosons. In particular, anomalous $H\gamma\gamma$ and $HZ\gamma$ couplings have already been considered in Z and Higgs boson decays [3], in e^+e^- collisions [3,4] and at $\gamma\gamma$ colliders [5].

In this letter, we make an exhaustive analysis of the anomalous Higgs boson contribution to the reaction $e^+e^- \rightarrow \gamma\gamma\gamma$ at LEP2 in order to extract information about possible anomalous $H\gamma\gamma$ and $HZ\gamma$ couplings. This process is an ideal place to look for deviations from the SM since it only involves well known purely QED contributions at tree level [6]. Our Monte Carlo analysis of the contribution $e^+e^- \rightarrow \gamma, Z \rightarrow \gamma H(\rightarrow \gamma\gamma)$ includes all the irreducible QED background and the respective interferences. After detailed study of the signal and background distributions, we find optimum cuts to maximize the signal to background ratio. We show how to use energy and invariant mass spectra of the final state photons in order to identify the presence of a Higgs boson and extract information about its couplings. Finally, we compare the bounds on the anomalous couplings that could be provided by this reaction with the present direct information on the triple vector boson coupling.

II. ANOMALOUS HIGGS COUPLINGS AND $e^+e^- \rightarrow \gamma\gamma\gamma$

A convenient basis of dimension six operators that parametrizes the deviations of the SM predictions in the bosonic sector was constructed by Hagiwara *et al.* [7]. They require the effective Lagrangian to be invariant under the local $SU(2)_L \times U(1)_Y$ symmetry and to be C and P even. Of the eleven operators \mathcal{O}_n that form this basis and induce the Lagrangian (1), five affect the Higgs boson interaction [3,7],

$$\begin{aligned}
\mathcal{O}_{BW} &= \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi, \\
\mathcal{O}_{WW} &= \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi, \\
\mathcal{O}_{BB} &= \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi, \\
\mathcal{O}_W &= (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi), \\
\mathcal{O}_B &= (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi),
\end{aligned} \tag{2}$$

where Φ is the Higgs doublet in the unitary gauge $\Phi = (v+H)/\sqrt{2} \begin{pmatrix} 0 & 1 \end{pmatrix}^T$, $\hat{B}_{\mu\nu} = i(g'/2)B_{\mu\nu}$, and $\hat{W}_{\mu\nu} = i(g/2)\sigma^a W_{\mu\nu}^a$, with $B_{\mu\nu}$ and $W_{\mu\nu}^a$ being the field strength tensors of the respective $U(1)$ and $SU(2)$ gauge fields, and $D_\mu = \partial_\mu + igT^a W_\mu^a + ig'Y B_\mu$, the covariant derivative.

The anomalous $H\gamma\gamma$ and $HZ\gamma$ couplings generated by (2), can be written in a compact form as,

$$\mathcal{L}_{\text{eff}}^H = g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu} + g_{HZ\gamma}^{(1)} A_{\mu\nu} Z^\mu \partial^\nu H + g_{HZ\gamma}^{(2)} H A_{\mu\nu} Z^{\mu\nu} , \quad (3)$$

where $A(Z)_{\mu\nu} = \partial_\mu A(Z)_\nu - \partial_\nu A(Z)_\mu$, and the coupling constants $g_{H\gamma\gamma}$, and $g_{HZ\gamma}^{(1,2)}$ are related to the coefficients of the operators appearing in (1) through,

$$\begin{aligned} g_{H\gamma\gamma} &= - \left(\frac{gM_W}{\Lambda^2} \right) \frac{s^2(f_{BB} + f_{WW} - f_{BW})}{2} , \\ g_{HZ\gamma}^{(1)} &= \left(\frac{gM_W}{\Lambda^2} \right) \frac{s(f_W - f_B)}{2c} , \\ g_{HZ\gamma}^{(2)} &= \left(\frac{gM_W}{\Lambda^2} \right) \frac{s(2s^2 f_{BB} - 2c^2 f_{WW} + (c^2 - s^2)f_{BW})}{2c} , \end{aligned} \quad (4)$$

with g being the electroweak coupling constant, and $s(c) \equiv \sin(\cos)\theta_W$. It is important to point out that the operators (2) does not induce any other new tree-level anomalous contributions besides the ones leading to the $H\gamma\gamma$ and $HZ\gamma$ interactions. In particular, 4-point anomalous couplings like $Z\gamma\gamma\gamma$ and $\gamma\gamma\gamma\gamma$ are absent.

In order to reduce the number of free parameters and, at the same time, relate the anomalous Higgs and the triple vector boson couplings, we make the natural assumption that all the coefficients of the dimension 6 operators have a common value f [8]. In this scenario, $g_{HZ\gamma}^{(1)} = 0$, and we can relate the other Higgs boson anomalous couplings with the coefficient of the usual anomalous vector boson coupling, $\Delta\kappa_\gamma = (M_W^2/\Lambda^2)f$, through,

$$\begin{aligned} |g_{H\gamma\gamma}| &= \frac{gs^2}{2M_W} |\Delta\kappa_\gamma| \simeq 9.2 \times 10^{-4} \text{ GeV}^{-1} \times |\Delta\kappa_\gamma| , \\ |g_{HZ\gamma}^{(2)}| &= \frac{gsc(1 - s^2/c^2)}{2M_W} |\Delta\kappa_\gamma| \simeq 1.2 \times 10^{-3} \text{ GeV}^{-1} \times |\Delta\kappa_\gamma| . \end{aligned} \quad (5)$$

We should point out that the anomalous vector boson couplings, like $\Delta\kappa_\gamma$, are basically unconstrained by the current high precision electroweak data. Presently, the best direct bound on $\Delta\kappa_\gamma$ was the one obtained by the CDF Collaboration [9] and constraints $-1.0 < \Delta\kappa_\gamma < 1.1$, at 95% C.L.. At LEP2, the angular distribution of final state fermions of the reaction $e^+e^- \rightarrow W^+W^- \rightarrow \ell\nu jj$ will be able to further restrict the allowed values of $\Delta\kappa_\gamma$ to $-0.19 < \Delta\kappa_\gamma < 0.21$, at 95% C.L. [8], for $\sqrt{s} = 176 \text{ GeV}$.

An interesting option to test the couplings described by (3) is through the reaction $e^+e^- \rightarrow \gamma, Z \rightarrow \gamma H(\rightarrow \gamma\gamma)$. In the SM, the process $e^+e^- \rightarrow \gamma\gamma\gamma$, at tree-level, is purely electromagnetic and is represented by the diagrams of Fig. 1(a). The inclusion of anomalous Higgs boson couplings gives rise to two additional contributions presented in Fig. 1(b). Since we are assuming that the Higgs boson coupling with fermions are the standard ones, *i.e.* proportional to m_f/v , we have neglected the corresponding contributions to this process.

This process has already been tested at the Z pole by LEP1 [10] which established an upper limit on the branching ratio $B(Z \rightarrow \gamma\gamma\gamma) < 1.0 \times 10^{-5}$. We found that this bound is not able to further restrict $\Delta\kappa_\gamma$ beyond the existent direct bounds [9]. For instance, for a 70 GeV Higgs, the above limit requires $\Delta\kappa_\gamma > 1.4$.

Here we make a detailed analysis for the two expected runs of LEP2 collider *i.e.* $\sqrt{s} = 176$ GeV, with $\mathcal{L} = 0.5 \text{ fb}^{-1}$, and $\sqrt{s} = 190$ GeV, with $\mathcal{L} = 0.3 \text{ fb}^{-1}$. We performed a Monte Carlo analysis using the package MadGraph [11] coupled to HELAS [12]. Special subroutines were constructed for the anomalous contributions which enable us to take into account all interference effects between the QED and the anomalous amplitudes. The phase space integration was performed by VEGAS [13].

In order to search for optimum cuts to maximize the signal to background ratio, we label the three final state photons as $\gamma_{1,2,3}$ according to decreasing value of their energy, *i.e.* $E_{\gamma_1} > E_{\gamma_2} > E_{\gamma_3}$. We start our analysis applying the following standard cuts on the events [14],

$$|\cos \theta_{ei}| \leq 0.97, \quad (6)$$

$$\theta_{ij} > 15^\circ, \quad (7)$$

$$E_{\gamma_i} \geq 5 \text{ GeV}. \quad (8)$$

where θ_{ei} is the angle between the photon i and the electron/positron beam direction, and θ_{ij} , is the angle between the photon pair (i, j) .

In Figures 2–4, we present our results for the photon spectra and angular distributions where only these cuts were applied. For illustrative purposes we consider a center-of-mass

energy of $\sqrt{s} = 176$ GeV, $M_H = 80$ GeV and an anomalous coupling $\Delta\kappa_\gamma = 1.5$.

In Fig. 2, we compare the normalized photon energy spectra of the signal and background, for the three photons. We can notice that for the background the energy of the two most energetic photons, E_{γ_1, γ_2} , tends to be close to $\sqrt{s}/2$, whereas the least energetic one, which is emitted by bremsstrahlung, is very soft. The signal is dominated by on-mass-shell $H\gamma$ production, with the subsequent decay $H \rightarrow \gamma\gamma$. The photon that does *not* come from the Higgs boson decay tends to have a two-body spectrum with energy $E_\gamma = (s - M_H^2)/(2\sqrt{s})$. This behavior is evident in Fig. 2 (a) and (b) where the peak at $E_\gamma \simeq 69.8$ GeV, is due to this “monochromatic” component. On the other hand, the softest photon, that always come from the Higgs boson decay, has an minimum energy given by $E_{\gamma_3}^{\min} \simeq M_H^2/(2\sqrt{s})$.

In Fig. 3, we present the normalized distribution of all photon pair angles. We can learn from Fig. 3 (a) that for the background the two most energetic photons are almost back-to-back, while for the signal this distribution is broader. The angular distributions for θ_{23} and θ_{13} reflect the existence of a minimum attainable angle between the two photons coming from the Higgs boson, $\theta_{\gamma\gamma}^{\min}(H) = 2 \arcsin(M_H/E_H)$.

In Fig. 4, we present the normalized angular distribution between the least energetic photon, γ_3 , and the electron beam. This distribution, for the background, is peaked in the forward and backward directions, while for the signal the least energetic photon, that always come from the Higgs boson decay, has a flat distribution with the beam. We omit the angular distributions between the other two photons with the beam since the behavior of the signal and background are quite similar.

An analysis of the angular distributions (Fig. 3) suggests that, if we require the maximum angle between any pair of photons to be less than 165° ($\cos\theta_{ij} > -0.97$), we can eliminate a large portion of the background events. When this cut is implemented the background falls from 699 fb to 203 fb while the signal remains almost the same, going from 36.1 to 30.7 fb. On the other hand, from the photon spectra (Fig. 2) we learn that cutting the maximum energy of each photon, for instance $E_\gamma < 70$ GeV, can significantly reduce the background. When we introduce this cut the total cross section of the background falls $\sim 90\%$, while

the signal is reduced by less than one half. Finally, the angular distribution of the softest photon with the beam suggests a cut $|\cos\theta_{e3}| \leq 0.8$, which reduces the background to the same order of the signal cross section. We should notice that the above cuts are less efficient for heavier Higgs bosons, restricting our analysis to a Higgs boson with mass up to 100 GeV.

From the above considerations, we have further imposed the energy cut,

$$5 \leq E_{\gamma_i} \leq 70 \text{ (80) GeV} , \quad (9)$$

for $\sqrt{s} = 176 \text{ (190) GeV}$, and the following angular cuts,

$$|\cos\theta_{e1,e2}| \leq 0.97 , \quad (10)$$

$$|\cos\theta_{e3}| \leq 0.80 , \quad (11)$$

$$15^\circ < \theta_{ij} < 165^\circ . \quad (12)$$

In Fig. 5, we present the double differential distribution of the energy and invariant mass, $d\sigma/dE_\gamma dM_{\text{inv}}$, for $\Delta\kappa_\gamma = 1.5$ and $M_H = 80 \text{ GeV}$. We have added up all events with E_{γ_i} , and $M_{\text{inv}_{jk}}$, for $i \neq j \neq k$. This Figure shows very clearly the enhancement due to anomalous Higgs contribution around $M_{\text{inv}} \simeq 80 \text{ GeV}$ and $E_\gamma \simeq 70 \text{ GeV}$.

III. CONCLUSIONS

In order to estimate the reach of LEP2 to disentangle the anomalous Higgs boson couplings via the reaction $e^+e^- \rightarrow \gamma\gamma\gamma$, we have evaluated the significance of the signal based both on the total cross section and on the Higgs boson enhancement in the $d\sigma/dE_\gamma dM_{\text{inv}}$ distribution. We have scanned the values of $\Delta\kappa_\gamma$, for $M_H = 80, 90$, and 100 GeV .

We show in Table I the minimum values of $\Delta\kappa_\gamma$ that can be probed in two runs of LEP2, for a center-of-mass energy of 176 and 190 GeV, with luminosities of $\mathcal{L} = 0.5$ and 0.3 fb^{-1} , respectively. The combined result for both runs is also presented. We required a 95 % of C.L. effect in the total cross section (σ_{tot}) and also in the double differential distribution ($d\sigma/dE_\gamma dM_{\text{inv}}$). In the latter case, we have added up the events in the eight 1 GeV bins around the expected Higgs boson signal.

We found that, if the anomalous coupling $|\Delta\kappa_\gamma| \gtrsim 0.8$ it will be possible to identify an anomalous Higgs boson in the range 80–100 GeV with 95 % C.L.. However, the signature of a heavier Higgs boson will not be so clear since the reaction $e^+e^- \rightarrow \gamma, Z \rightarrow \gamma H(\rightarrow \gamma\gamma)$ is particularly important when the Higgs boson is almost on-mass shell.

In conclusion, the search for anomalous Higgs boson couplings at LEP2 provides a complementary way to probe effective Lagrangians that are low-energy limit of physics beyond the SM. We have shown that the study of the process $e^+e^- \rightarrow \gamma\gamma\gamma$ is able to improve the present limits on the anomalous vector boson couplings that are concomitantly involved in operators like (2) that modify the bosonic sector of the Standard Model.

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FIGURES

FIG. 1. Feynman diagrams for $e^+e^- \rightarrow \gamma\gamma\gamma$

FIG. 2. Normalized photon energy distribution $(1/\sigma)d\sigma/dE_{\gamma_i}$ ($i = 1, 2, 3$), for the anomalous (solid line) and standard model (dashed line) contributions. We assumed $\Delta\kappa_\gamma = 1.5$ and $M_H = 80$ GeV.

FIG. 3. Normalized angular distribution between photons $(1/\sigma)d\sigma/d\cos\theta_{ij}$. The conventions are the same as in Fig. 2.

FIG. 4. Normalized angular distribution of the softest photon with the beam $(1/\sigma)d\sigma/d\cos\theta_{e3}$. The conventions are the same as in Fig. 2.

FIG. 5. Double photon energy-invariant mass distribution $d\sigma/dE_\gamma dM_{inv(\gamma)}$, for the process $e^+e^- \rightarrow \gamma\gamma\gamma$, for the background (shaded histogram) and for the signal (white histogram) with $\Delta\kappa_\gamma = 1.5$ and $M_H = 80$ GeV.

TABLES

	$\sqrt{s} = 176 \text{ GeV}$		$\sqrt{s} = 190 \text{ GeV}$		Combined	
$M_H \text{ (GeV)}$	σ_{tot}	$d\sigma/dE_\gamma dM_{\text{inv}}$	σ_{tot}	$d\sigma/dE_\gamma dM_{\text{inv}}$	σ_{tot}	$d\sigma/dE_\gamma dM_{\text{inv}}$
80	1.32	0.89	1.49	0.96	1.18	0.78
90	1.42	0.95	1.56	0.97	1.26	0.81
100	1.64	1.04	1.70	1.01	1.41	0.87

TABLE I. Values of $\Delta\kappa_\gamma$, corresponding to 95 % C.L. from the total cross section σ_{tot} , and from the double distribution $d\sigma/dE_\gamma dM_{\text{inv}}$, for the $\sqrt{s} = 176$ and 190 GeV runs of LEP2.

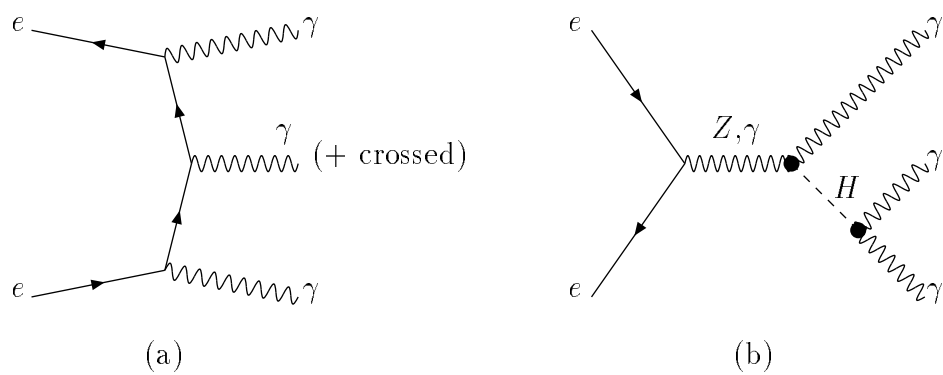


Fig. 1

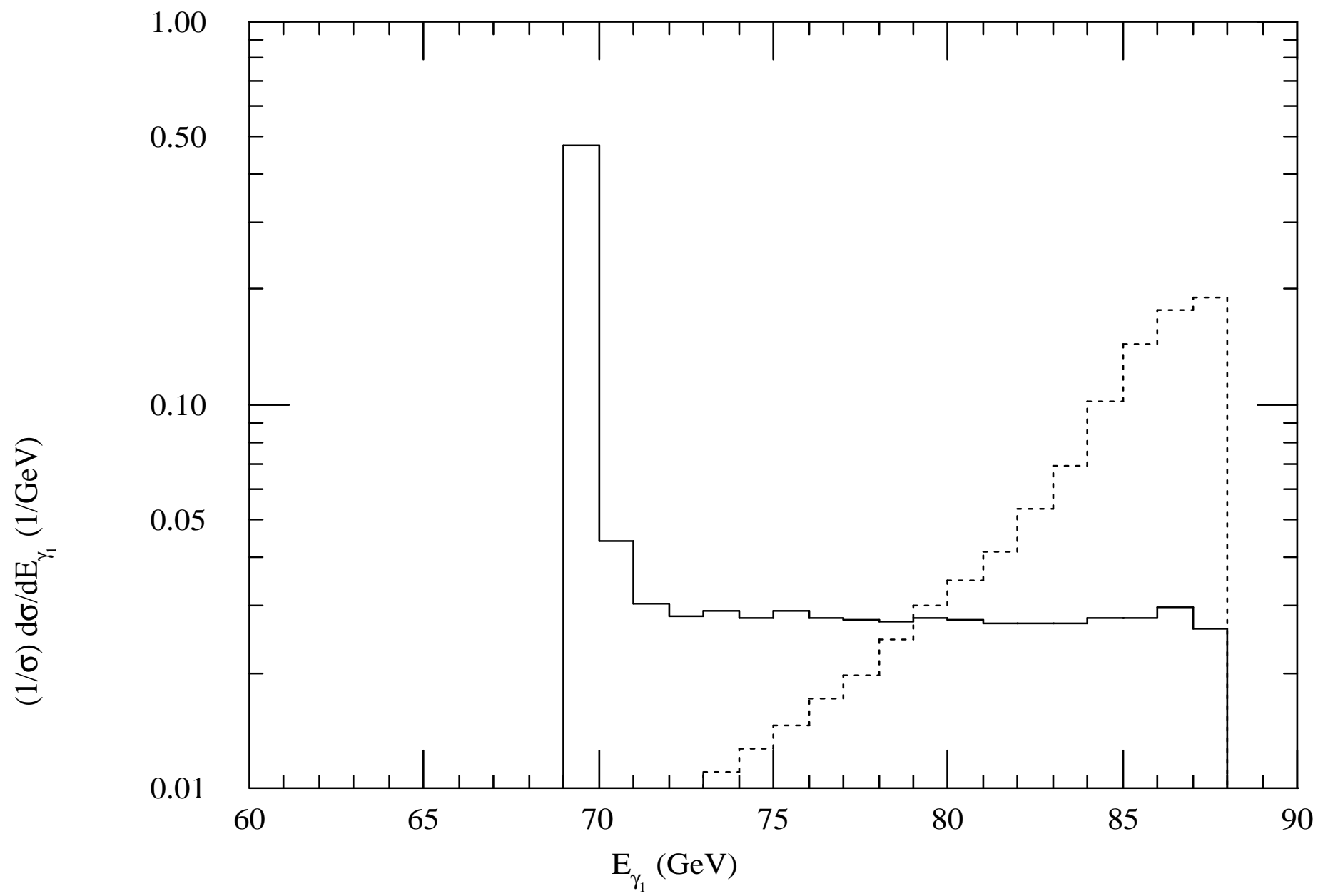


Fig. 2 (a)

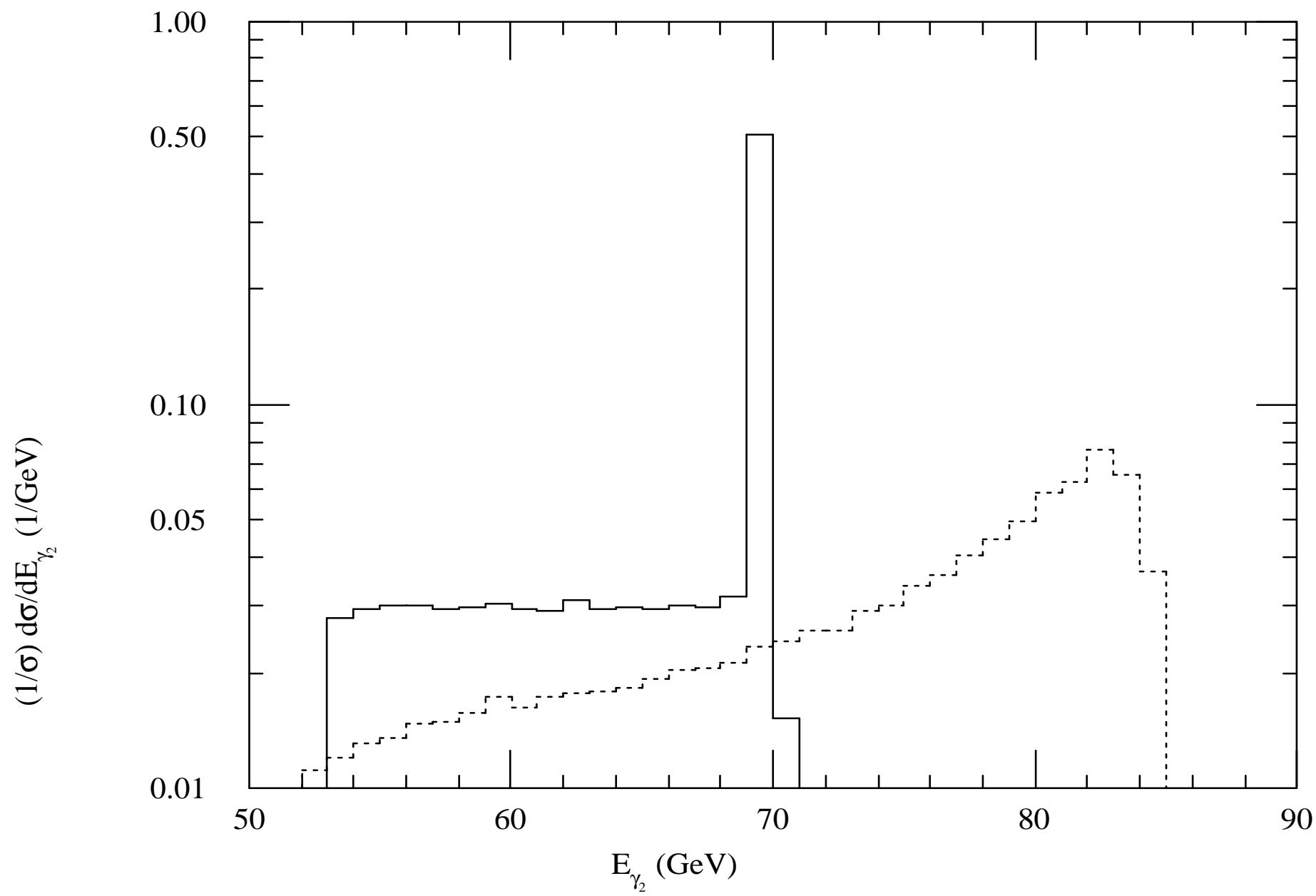


Fig. 2 (b)

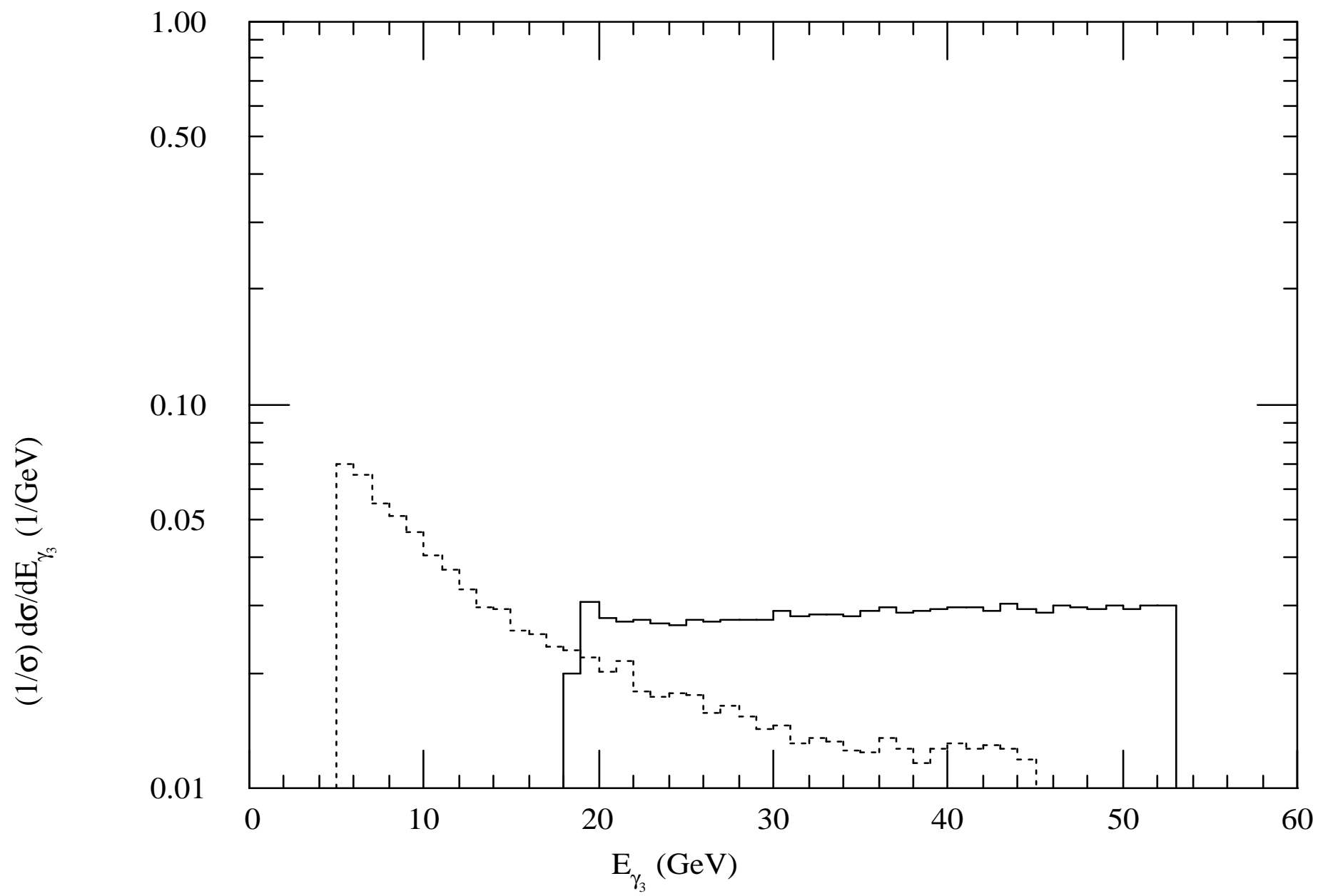


Fig. 2 (c)

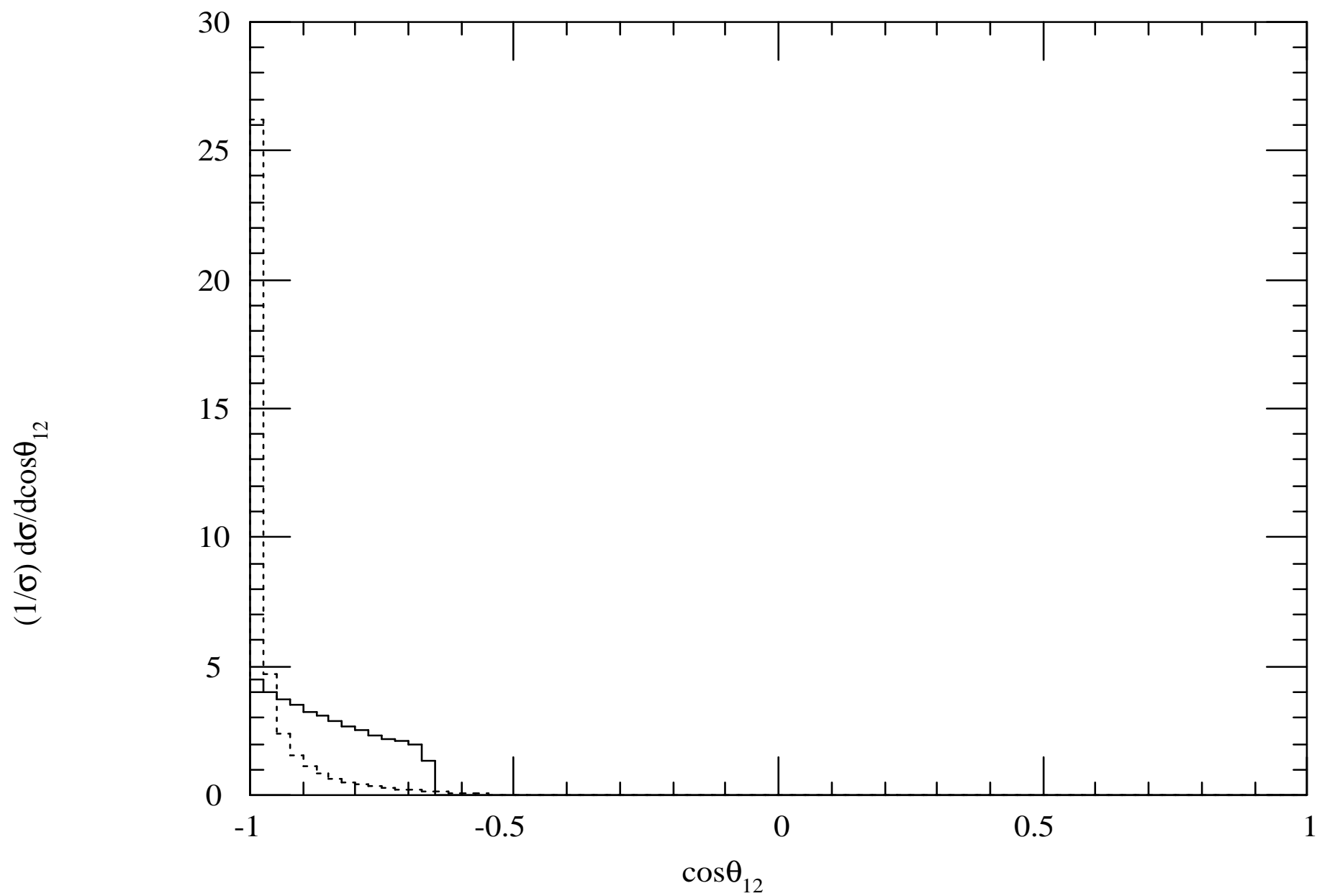


Fig. 3 (a)

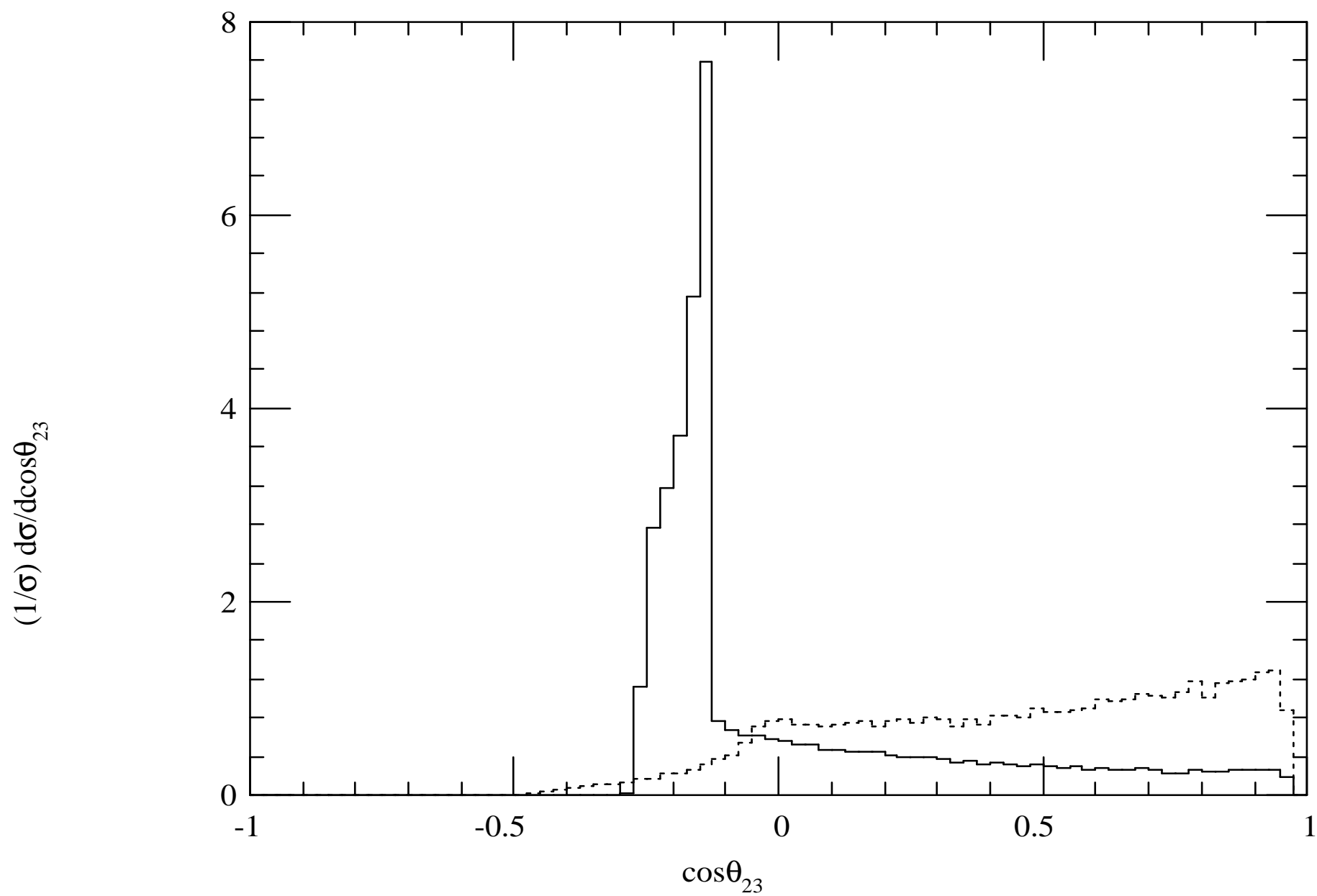


Fig. 3 (b)

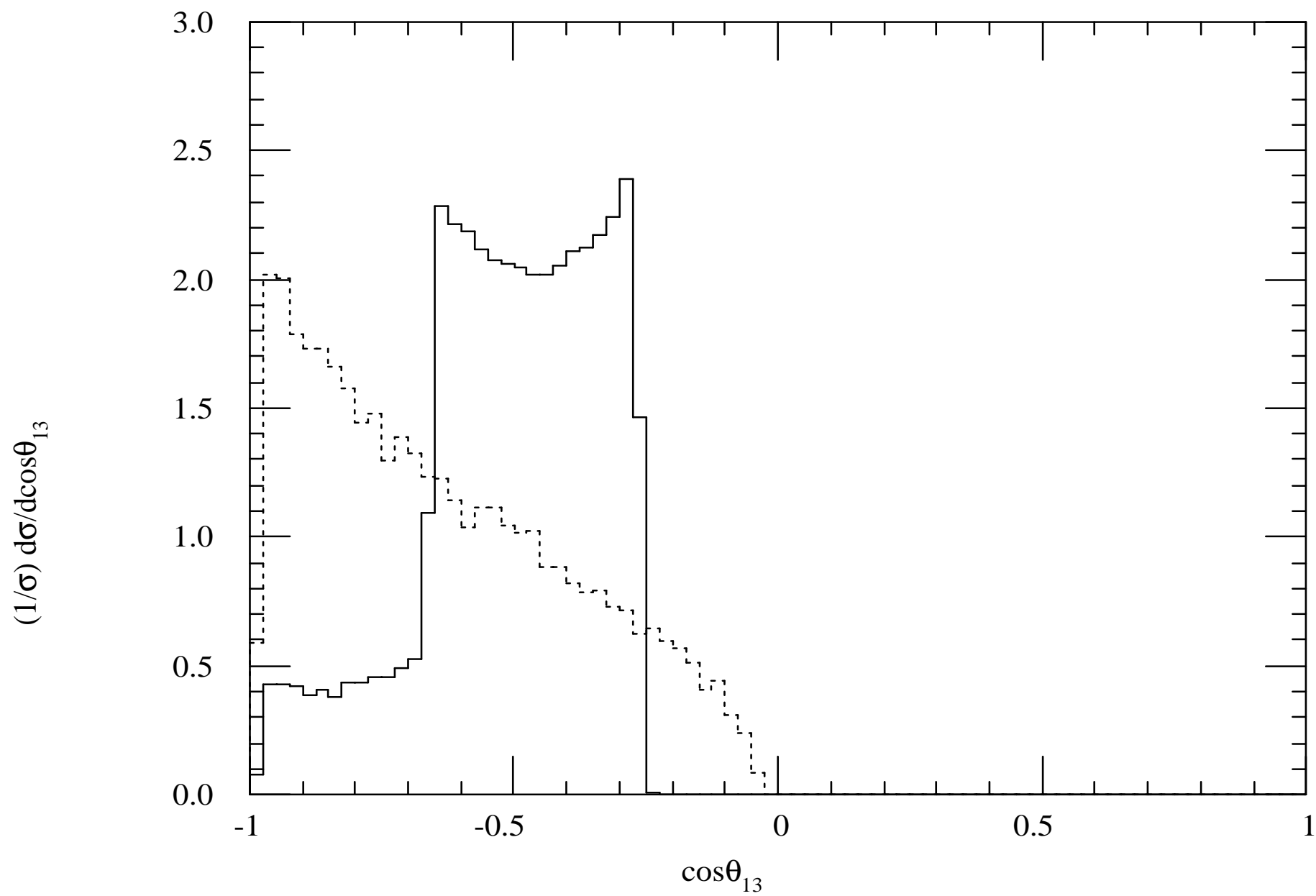


Fig. 3 (c)

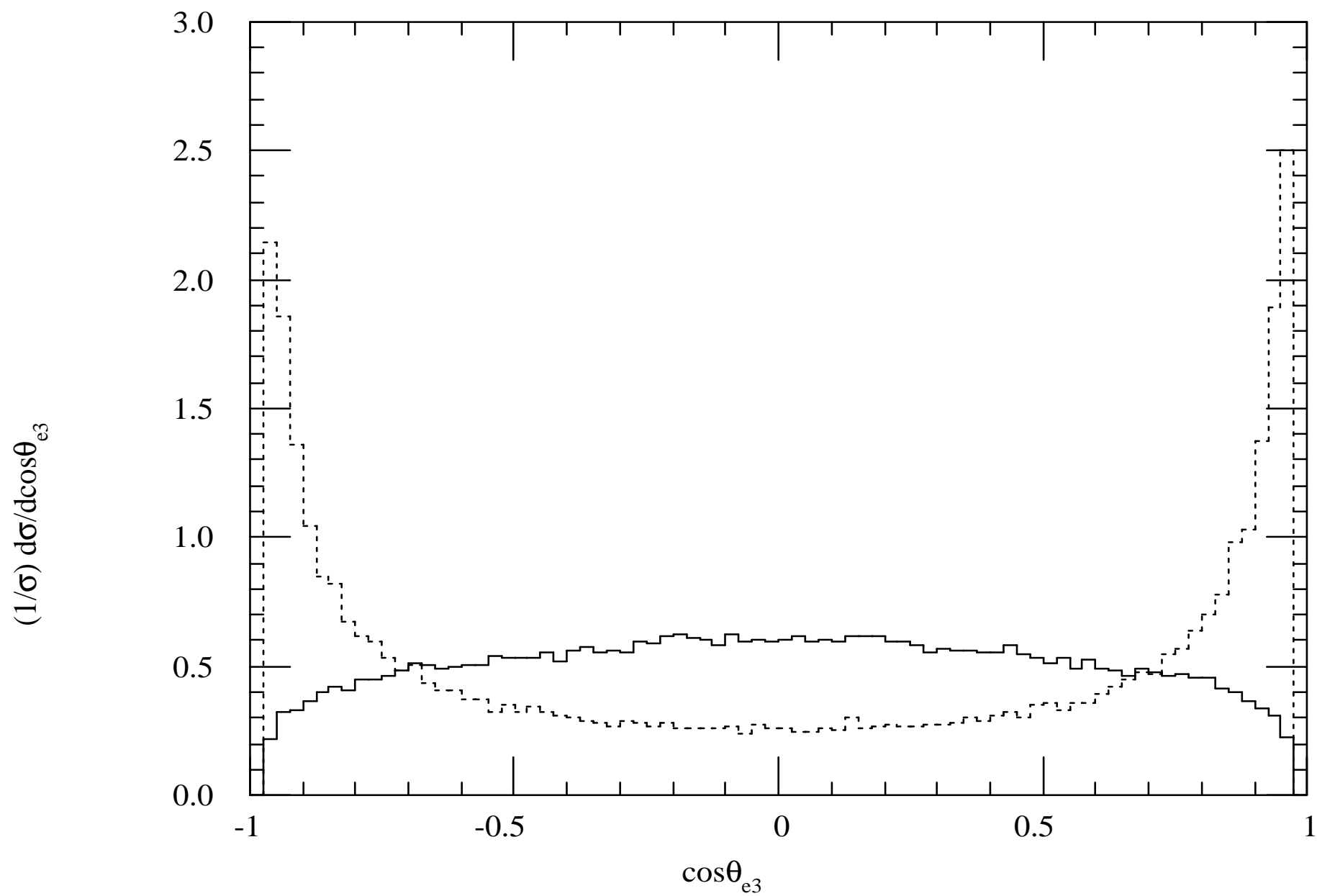


Fig. 4

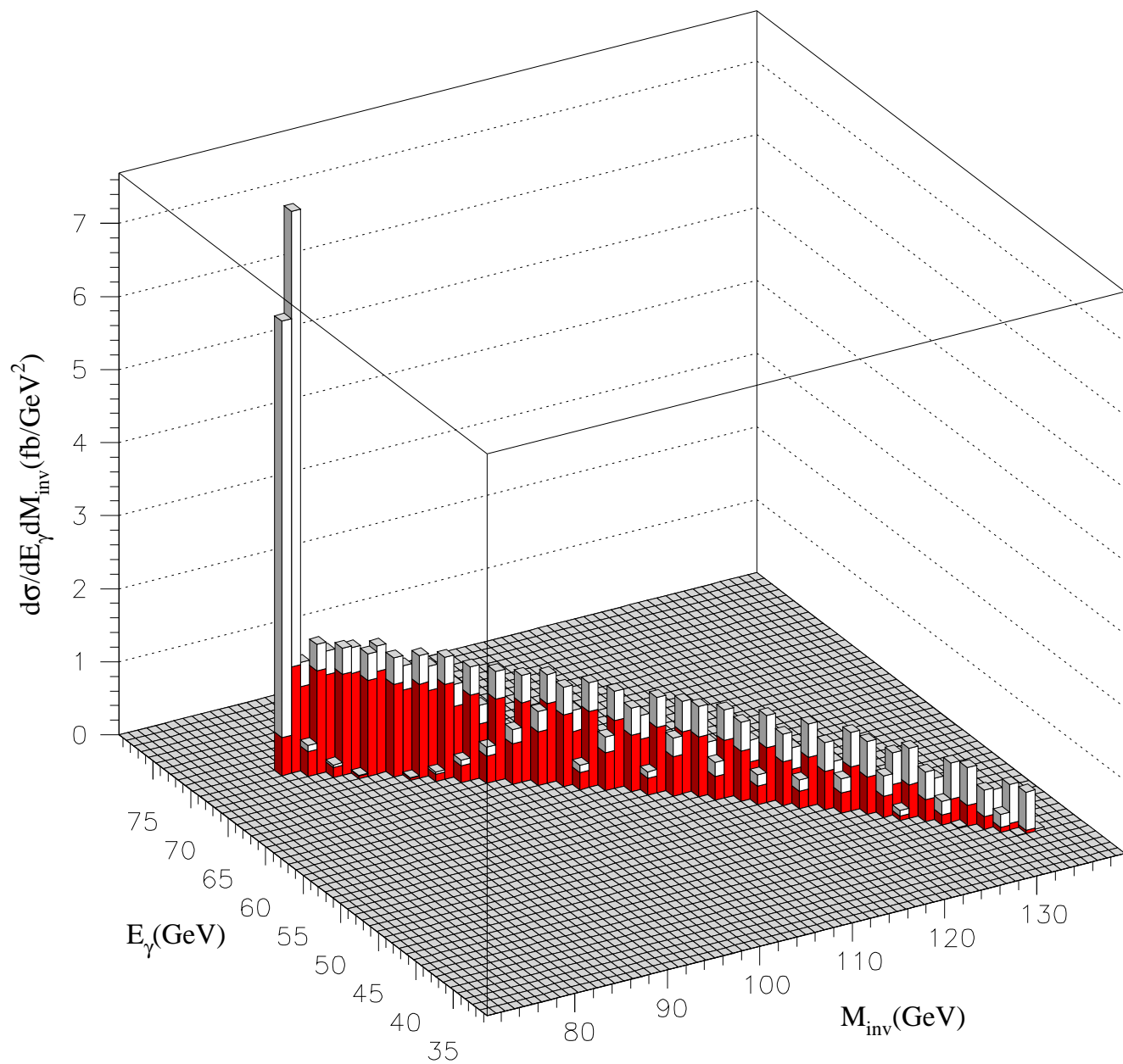


Fig. 5